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INTEGRATION OF AUTOMATIC CALIBRATION
SYSTEM FOR VEHICLE INSTRUMENTATION

Phase C-3 Report

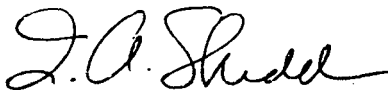
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INTEGRATION OF AUTOMATIC CALIBRATION
SYSTEM FOR VEHICLE INSTRUMENTATION

Phase C-3 Report

16 July 1965

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ABSTRACT

This Final Report covers Phase C-3 of Contract NAS 8-11705 as performed by Northrop Nortronics. Phase C-3 is a study to investigate future system checkout requirements, considering the application of the Automatic Calibration Technique (ACT) concept to active and passive checkout of remote systems. ACT, by its general requirement, is an active technique; the normal signal flow being interrupted and replaced by known inputs. In this report, a comparison is made between present methods of computer checkout and ACT. Onboard programming techniques are described to show how initiation and identification of calibration can be provided independent of ground-based computer commands. Advantages and disadvantages of both ground and onboard checkout are discussed. On manned spacecraft, it is felt that an onboard computer for evaluating only those signals for safety and control of the capsule should be provided. Applications of ACT to both manned and unmanned vehicles and their operation in relation to ground-based stations are discussed. Also included in this report is a brief review of the ACT and a discussion of active and passive checkout. Recommendations are made on how ACT should be applied to future vehicles, both manned and unmanned.

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DEFINITIONS

ACT	Automatic Calibration Technique
Calibration	Measurement of values for high and low checkpoints and application of correction to obtain predetermined values either by adjustment or ACT
Calibration checkpoints	Predetermined values that lie on the calibration curve (approximately 10 percent and 80 percent of full scale)
Calibration curve	Laboratory obtained curve that provides specific data on the operation of the components
Corrected measurement	Computer processed value in which instrumentation error is calibrated to reflect actual sensor value
DDAS	Digital Data Acquisition System
Drift	Change in the dynamic amplification factor
ESE	Electronic Support Equipment
GSE	Ground Support Equipment
Instrumentation	Items of the Saturn system used to transmit intelligence concerning vehicle performance (includes sensors, signal conditioners, telemetry, and associated GSE)

IU	Instrumentation Unit
KSC	Kennedy Space Center, Cocoa Beach, Florida
Modes:	
Run	Signal flows from sensor through signal conditioner constituting a normal measurement
High-Calibrate	Programmed known input \approx 80 percent of full scale
Low-Calibrate	Programmed known input \approx 10 percent of full scale
MSFC	Marshall Space Flight Center, Huntsville, Alabama
Offset	A quality of displacement that affects all values equally
Predicted values	Values of data that theoretically lie on the calibration curve
RACS	Remote Automatic Calibration System
Software	The intelligence to exercise the hardware to make the computer system operate.

SECTION 1
SUMMARY

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This report covers the investigations of future system checkout requirements while considering the application of the Automatic Calibration Technique (ACT) concept to active and passive checkout of remote systems. Computer operation using the ACT is described. For optimum efficiency, the RCA 110A computer is too slow for the considerations involved. Smaller and faster off-the-shelf computers, under control of the RCA 110A, could be used for the ACT, releasing the RCA 110A for other checkout routines. Onboard computers are discussed; it is felt that a small computer, used only for safety and control measurements pertaining to the spacecraft capsule in manned vehicles, would be advantageous. This computer would be redundant to one on the ground, but would be utilized strictly for astronaut use. No other instrumentation checkout computer would be required onboard.

Also discussed is the utilization of an onboard programmer, which is set into operation by a single pulse from the onboard command receiver.

Recommendations are made in section 10.

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SECTION 2

INTRODUCTION

This is the third and final formal report defining the progress achieved under Contract NAS 8-11705 by Nortronics, a Division of the Northrop Corporation.

During Phase A through Phase C-2 of the Contract, Nortronics developed the Automatic Calibration Technique (ACT), a concept for checkout of the Saturn Program Instrumentation utilizing existing equipment and employing computer control and calculation. Work accomplished during these phases was covered in NSS Report No. 3096A, dated 5 February 1965, and NSS Report No. 3224, dated 18 March 1965. This report covers Phase C-3 of the above-mentioned contract. The Phase C-3 task was to investigate future system checkout requirements, considering the application of the ACT concept to active and passive checkout of remote systems.

ACT, after a one-time system adjustment, provides data correction in its calibration scheme instead of the time-honored method of component readjustment. Known inputs are programmed into the signal conditioners; the values at the system outputs, corresponding to the known inputs, are measured and compared to the theoretical or predetermined outputs. Data correction factors then are computed for application to measured engineering parameters. The application of the correction factors can be made in real-time or during subsequent data reduction.

A review of ACT is presented in section 3 to help the reader understand the application of it as discussed herein.

SECTION 3
REVIEW OF THE AUTOMATIC CALIBRATION TECHNIQUE

The Automatic Calibration Technique (ACT) employs computer programming to:

- (1) Interrogate all RACS-controlled Saturn instrumentation data channels (in order or on command)
- (2) Measure data channel outputs
- (3) Compare the measured outputs with predetermined, predicted values
- (4) Determine gain and/or offset correction factors (for each channel requiring same)
- (5) Store the correction factors
- (6) Apply the correction factors automatically when the channels are re-interrogated in the run mode.

Thereby, ACT provides continuous, updated data regarding the instantaneous status of the Saturn instrumentation.

ACT, as applied to d-c signal conditioners, evolved during the first phase of this study program, was chosen and proven (mathematically/graphically) during the second phase, and was expanded in concept to apply to all other Saturn signal conditioners during Phase C-1.

ADVANTAGES AND FEATURES

The 10 prime advantages provided by ACT are listed below.

- (1) Reduces checkout and calibration time and total man-hours
- (2) Minimizes adjustments
- (3) Implements easily
- (4) Provides complete and flexible historical data
- (5) Simplifies standardization of data
- (6) Allows for modernization of equipment
- (7) Is fully automatic
- (8) Uses known-input facility
- (9) Provides quick-calibration capability
- (10) Optimizes calibration timing.

ACT REQUIREMENTS

To implement ACT, four system requirements must be met. These are described in the following paragraphs.

Inputs

A means of inserting known, stable inputs into the signal conditioners is required. For a d-c signal conditioner (or circuit that can contain a d-c offset), two calibration checkpoints are necessary. These checkpoints should be separated by at least 60 percent of full scale for optimum accuracy. An a-c conditioner (or circuit that cannot contain any offset) requires only one calibration checkpoint.

On vehicles as complex as the Saturn, it is impossible to excite all of the various sensors by their regular stimuli for calibration. Therefore, calibration voltages are derived, within each of the signal conditioners, that synthetically represent measurement parameters. ACT can correct any instrumentation loop errors that result between the input to the signal conditioner and the computer (it cannot correct for errors in the sensor). The sensor output, when connected to the signal conditioner, is checked against the output for its expected environment.

Linearity

All components within the ACT calibrated loop must be linear throughout the operating range of that section of the loop (from the input to the signal conditioner, through the conditioner, and up to the input to the computer).

Arithmetic Unit

A computer-type device, with complete arithmetic capabilities, is required to compute and apply the necessary data-correction factors.

System Accuracy

System accuracy is dependent upon ACT being able to measure, maintain, and apply the specific inputs. System accuracy also depends upon the number of bits that represent a data word processed by the computer. Any component, of which the linearity deviates from a straight line, affects that portion of the system by an amount up to the limit of the excursion. Mathematically, the accuracy can be no better than $1/2^n$, where n equals the number of bits in a binary word. Thus, if a data word contains 10 bits, the best attainable accuracy is 0.1 percent.

D-C SIGNAL CONDITIONER CALIBRATION

This paragraph describes a typical d-c signal conditioner calibration procedure. It is valid for all drifts and/or offsets that are considered linear. Typically, to perform d-c signal conditioner checkout and/or calibration, the computer programs the Remote Automatic Calibration System (RACS) and DDAS to obtain high- and low-calibration checkpoints for the channel in question. The DDAS outputs for both checkpoints are fed to the computer and compared with the appropriate predicted calibration-curve checkpoint values that were stored in the computer memory. The computer generates correction factors and places these factors in storage for modification of sensor-derived data (run mode) to provide true data, when interrogated (either during checkout and calibration or actual vehicle flight).

Figure 1 depicts a predicted (calibration) curve and a curve representing the measured values. The measured values are those values that are the actual output of a signal conditioner. These measured values may differ from the calibration values by either a drift of the signal conditioner gain, an offset, or a combination of the two. ACT then applies correction factors to the measured values of each given sensor to provide correspondingly corrected data lying on the calibration curve.

GRAPHICAL SOLUTION

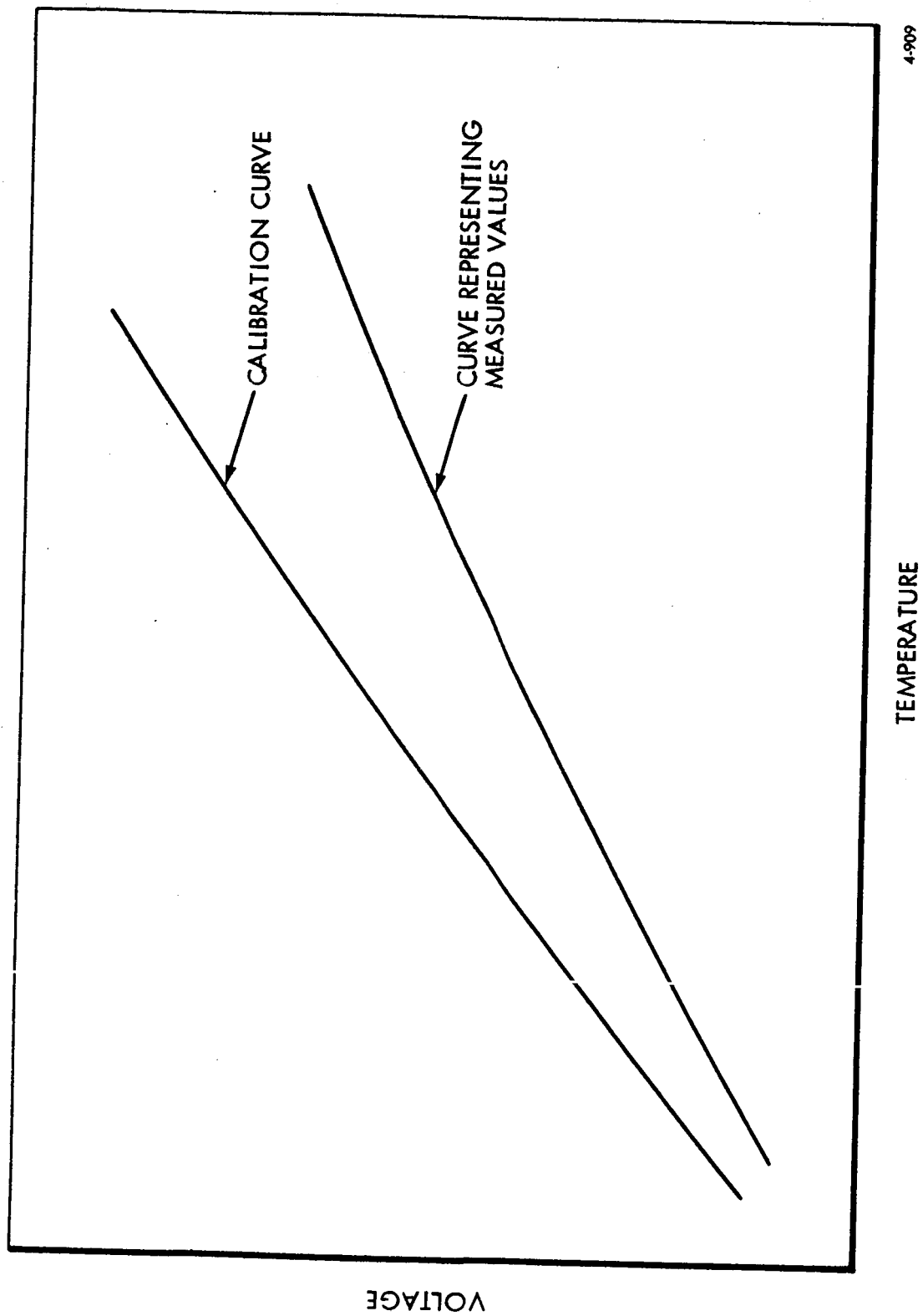
To best illustrate ACT, a graphical solution is depicted in figure 2. On the left-hand curve, point X_1 represents the predicted high checkpoint, X_2 represents the predicted low checkpoint, Y_1 locates the measured high checkpoint, and Y_2 locates the measured low checkpoint.

The right-hand curve provides a comparison of the measured and predicted values. The predicted values increase along the abscissa and the measured values increase along the ordinates such that $X_1 Y_1$ and $X_2 Y_2$ represent two points. A line is drawn through the two points $X_1 Y_1$ and $X_2 Y_2$ representing a conversion curve of predicted versus measured values. For any point Y_0 , representing a measured value, there is a corresponding point X_0 , representing a point on the calibration curve.

MATHEMATICAL SOLUTION

The graphic solution determining the correction factor to apply to measured data provides a simple explanation of ACT, but is not applicable to computer computation. Therefore, the following mathematical solution is provided.

A straight line conversion curve can be generated such that for any measured value, Y_0 , there is a corresponding corrected value X_0 . The straight line conversion curve is defined by the relationship of the measured and predicted checkpoints as described for the graphical solution.



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Figure 1. PREDICTED AND MEASURED VALUES COMPARED

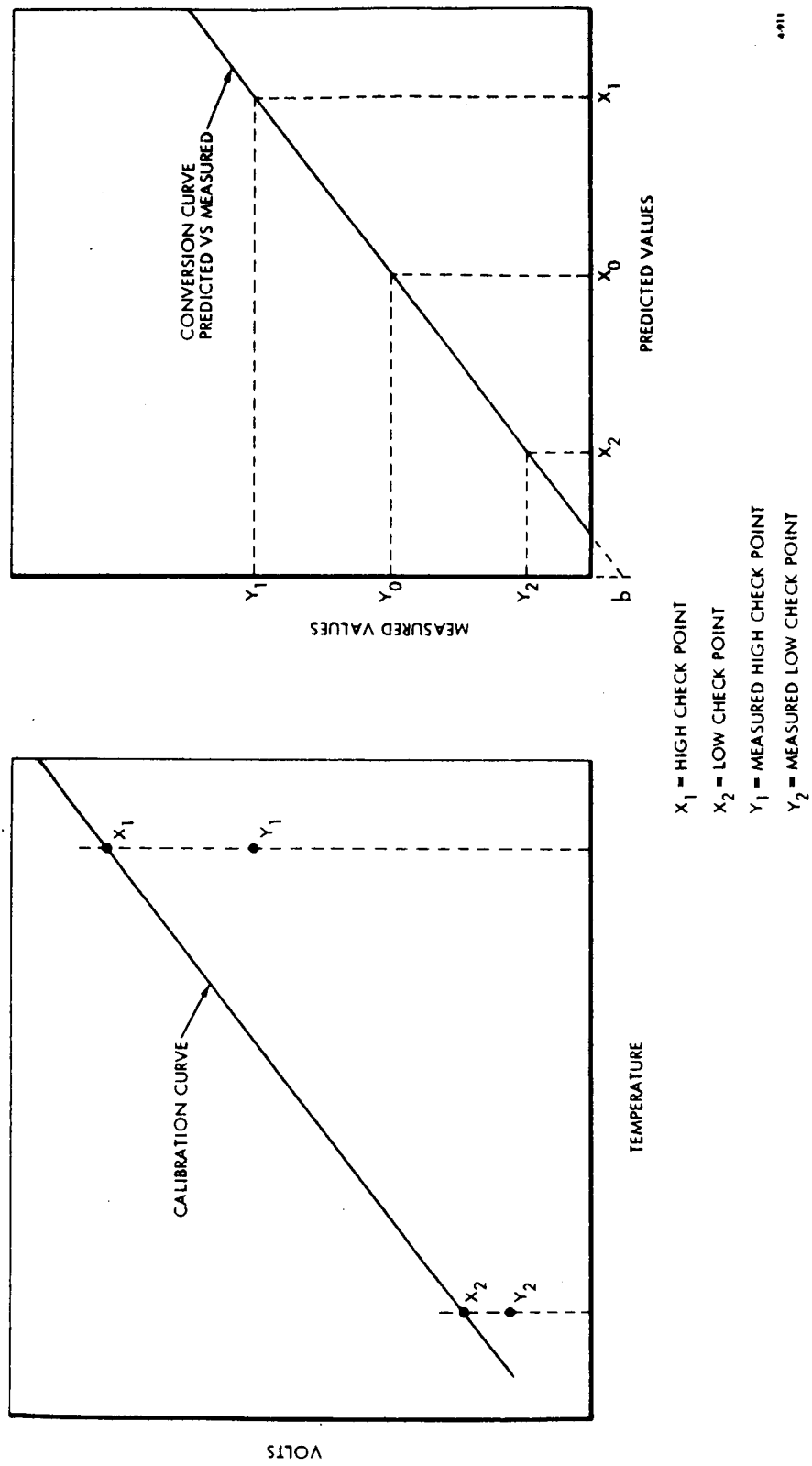


Figure 2. APPLICATION OF CONVERSION FACTOR

The equation of a line is $Y = mX + b$

where: X and Y are coordinates of any point on the line

m = the slope of the line

b = the ordinate intercept of the line

Figure 2 depicts a straight line conversion curve running through points X_1 Y_1 and X_2 Y_2 and intersecting the ordinate at point b .

Let X_1 = the predicted high checkpoint value

X_2 = the predicted low checkpoint value

Y_1 = the high measured checkpoint value

Y_2 = the low measured checkpoint value

Y_0 = any measured value

To solve for X_0 , the corrected value of the measured value Y_0 , the following computations are made:

$$Y = Y_1 - Y_2$$

$$X = X_1 - X_2$$

$$\text{Slope } m = \frac{\Delta Y}{\Delta X} = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$\text{Ordinate intercept, } b = Y_1 - mX_1$$

Both the values of the slope, m , and the ordinate intercept, b , can be computed when the predicted and measured values of the checkpoints are known. From these values:

$$X_0 = \frac{Y_0 - b}{m}$$

ACT measures the high and low checkpoints, obtains the predicted checkpoint values from computer memory, and solves for the slope and ordinate intercept of the conversion factors. The conversion factors are then applied to run data by the computer to determine the corrected values.

A-C SIGNAL CONDITIONER CALIBRATION

Much like the d-c procedures, a-c signal conditioner calibration is achieved by generating a conversion curve, but with only one calibration point (as opposed to the two required for the d-c application). The following discussion of characteristics is based upon the completion of the typical MSFC procedure for receiving tests, generation of a calibration curve, and verification of the unit.

The a-c signal is superimposed on a 2.5-volt d-c level at the signal conditioner output; this d-c level acts as a "carrier" for the a-c signal. The 2.5-volt amplitude was chosen since it was the minimum level that would not clip the a-c information. Capacitors in the SS/FM input stages block the dc, negating the possibility of offset (a problem with the d-c system). When the a-c signal conditioner is used on the FM/FM channels such as a measurement of the F1-601 Flow Rate for Boiler Inlet Water on Saturn IB, the 2.5-volt bias becomes critical should any high a-c signal levels occur. Clipping will occur if the bias voltage differs from 2.5 volts with a peak-to-peak input greater than 5 volts.

Only one calibrate point is required because the d-c-type offset problem does not exist. Thus, one calibration point and the zero-zero point define the slope of the a-c signal conditioner conversion curve. The slope, yielding gain for that particular amplifier at any time when compared with the calibration curve, defines the instantaneous gain change or drift. Averaged over a particular period, the drift is compensated for by the computer that inserts an appropriate correction factor (which returns the amplifier data to its calibration-curve parameters).

The majority of the a-c signal conditions are transmitted over the SS/FM link normally not interfacing with the computer. MSFC procured a Hewlett-Packard 2401 digital voltmeter with an HP2410 a-c converter. These units, when coupled with appropriate switching circuitry, will enable the output from the SS/FM decommutators to be fed to the computer.

SECTION 4

ACTIVE AND PASSIVE CHECKOUT

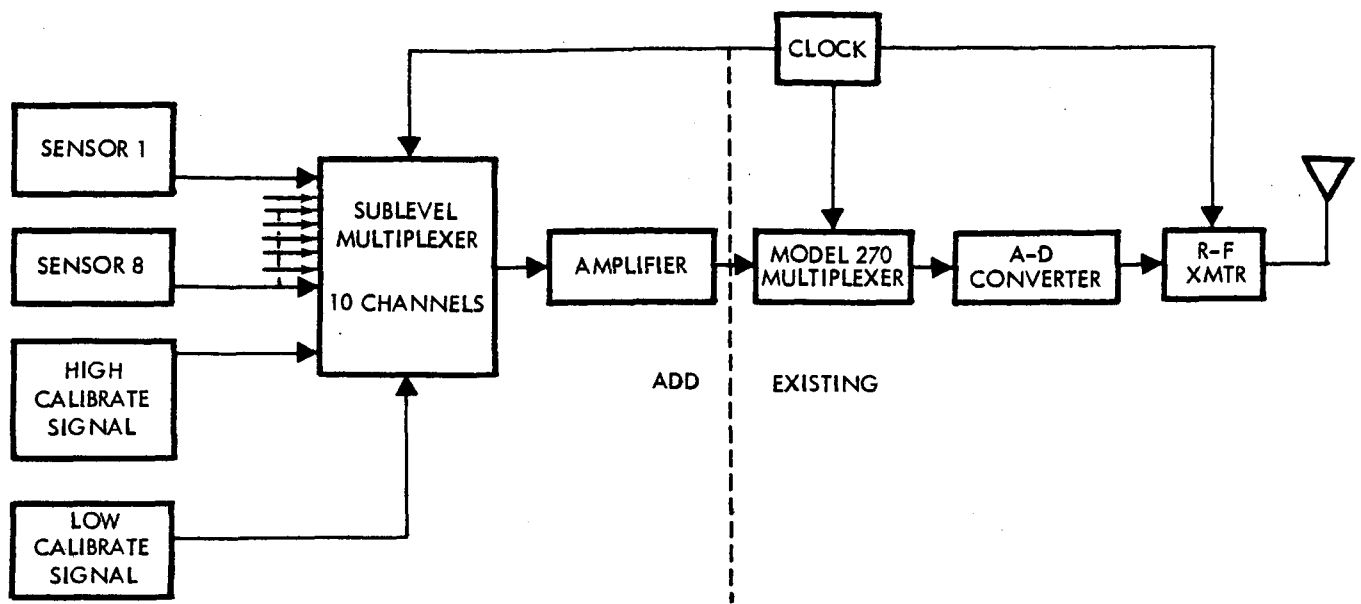
The terms active and passive, when associated with checkout systems, have had various meanings. The generally accepted connotation (used herein) is that active checkout is where the normal signal flow is interrupted and replaced with or acted upon by generated stimuli. Passive checkout is where the normal signal flow is not interrupted or acted upon by external stimuli.

ACT, by its general requirement, is an active technique. To use ACT, two known inputs are required. These known inputs, checkpoint values, replace the normal signal flow to provide data for determining correction factors.

However, the above does not preclude a form of passive checkout when time-sharing data transmission systems are used. This time-sharing permits multiplexing of sensors and checkpoint values into a common signal amplifier.

The multiplexer can be synchronized with a Model 270 Time Divisional Multiplexer, and its output connected to one of the primary channels of the Model 270. Since synchronization exists, each time the DDAS wave train scans the Model 270 primary channel, the external sublevel multiplexer will progress through its scan of the sensors and checkpoint values.

Figure 3 shows a block diagram of the proposed sublevel multiplexer system that allows passive checkout and calibration. Eight sensors, plus high and low checkpoints, are inputted into the multiplexer. The inputs are scanned in sequence to provide a series of 10 segments that are amplified and fed to a primary channel of a Model 270 multiplexer. The Model 270 multiplexer inserts the data into the proper slots of the PCM wave train for conversion to digital format for transmission to the ground receiving station.



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Figure 3. PASSIVE CALIBRATION TECHNIQUE

Once received on the ground, the computer selects the checkpoint data words and generates the signal amplifier correction factors. These correction factors then can be applied to the eight sensor data words associated with the checkpoint words to provide true sensor data.

There are certain limitations encountered when using this sublevel multiplexer. Because all sensor outputs are amplified by the same amplifier, the sensors connected to a particular sublevel commutator should have approximately equal output ranges. Numerous measurements presently require that the sensor and signal conditioner be calibrated as one unit under this condition. If the sensor is replaced, it is mandatory to replace the signal conditioner. Using the sublevel multiplexer under conditions where sensors and signal conditioners must be calibrated together might require that a whole combination of sensors be calibrated through one signal conditioner. This creates an undesirable feature in that if one component is replaced, the entire group of sensors associated with the signal conditioner would require replacement.

In reviewing the measurement requirements on Saturn IB, it appears that temperature measurements on the booster would be the most feasible to combine into a common

signal conditioner. This is due to the fact that the eight rocket motors and peripheral equipment essentially have the same instrumentation.

The benefits to be derived from this type of passive measurement system are questionable when associated with stages other than the booster. It is true that power requirements for calibration and operation are decreased, but prior to launch, this is not a real problem. To be of value, there must be sufficient measurements that have sensors of identical output ranges that are independent, calibration-wise, from the signal conditioner. Instrumentation requirements for stages other than Saturn IB boosters and the IU unit are not available.

SECTION 5

COMPUTER FLOW

Currently, the DDAS onboard system generates an 1800-word wave train. This wave train is transmitted to the ground DDAS four times a second either by a hardwired 600-kc carrier (prior to launch) or by r-f link. The DDAS interfaces with the computer through 13-bit address lines, 40-bit data lines, and a data ready line. The computer originates a 13-bit address, and when coincidence occurs between the address and the DDAS internal counters, four data words (40-bits in parallel) and a "data ready" signal appears on the DDAS output register lines.

Data can be transferred at the rate of four words every 1112 microseconds, provided the computer programming is arranged in the proper sequence. With an acquisition rate of four words every 1112 microseconds, the computer can acquire all information in 500 milliseconds (two wave trains).

The computer for the Saturn program at Kennedy Space Center is the RCA 110A. This computer, while having the capability of control and evaluation of many functions, is relatively slow in performing arithmetic computations. The word cycle time of the RCA 110A is 28.85 microseconds. This cycle time prevents the computer from determining or applying ACT correction factors in real time. Additional time factor limitations are caused by RACS programming and readout of the data. Figure 4 shows the computer flow for determining and applying the correction factors. The correction factors require the measurement of two known checkpoint values prior to their computation. These checkpoints are selected by the computer through the RACS. RACS requires the application of control signals for a minimum of 50 milliseconds and a maximum of 250 milliseconds to program in one checkpoint. Because of the RACS operation time, it is preferred to obtain all high checkpoint values prior to obtaining the low checkpoint values. For example, if all high checkpoints were programmed in

sequentially, 1.6 seconds would be required for 500 channels; but if the high checkpoint and then the low checkpoint are programmed for one channel, it would take 300 seconds for 500 channels.

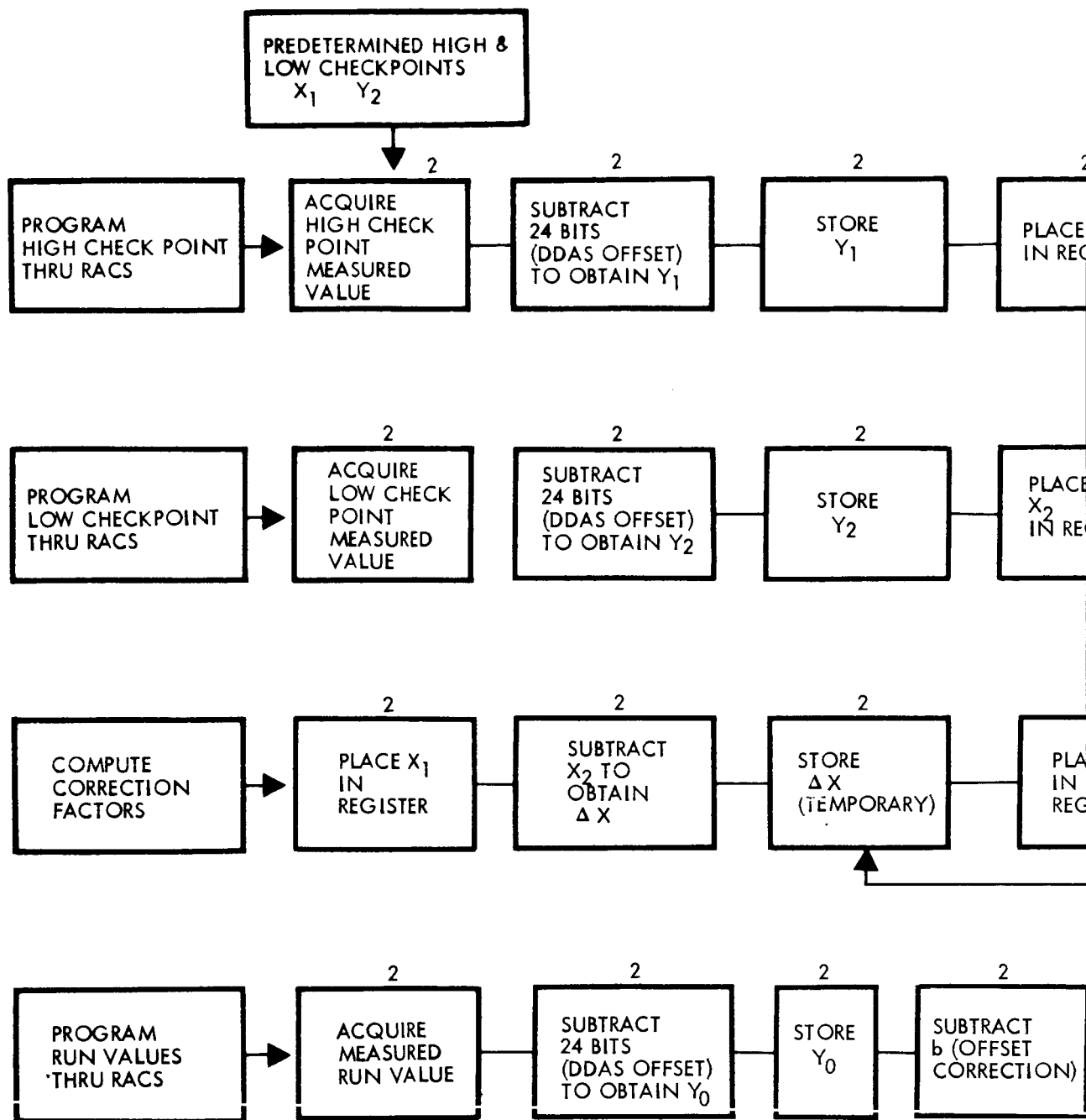
The following describes the operation and time involved for the RCA 110A computer to process one signal measurement channel (refer to figure 4).

The following connotations are used:

- X_1 = Predetermined high checkpoint value
- X_2 = Predetermined low checkpoint value
- Y_1 = Measured high checkpoint value (DDAS offset removed)
- Y_2 = Measured low checkpoint value (DDAS offset removed)
- m = Gain correction factor
- b = Offset correction factor
- Y_0 = Measured run value (DDAS offset removed)
- X_0 = Corrected run value

Prior to the performance of a calibration run, the predetermined high and low checkpoint values X_1 and X_2 must exist in the computer memory. These values will remain fixed for a given signal condition. In addition, the run value high and low tolerance limits are required in memory. The capability for changing these latter limits should exist so that as the sensor environment changes, the limits can be changed.

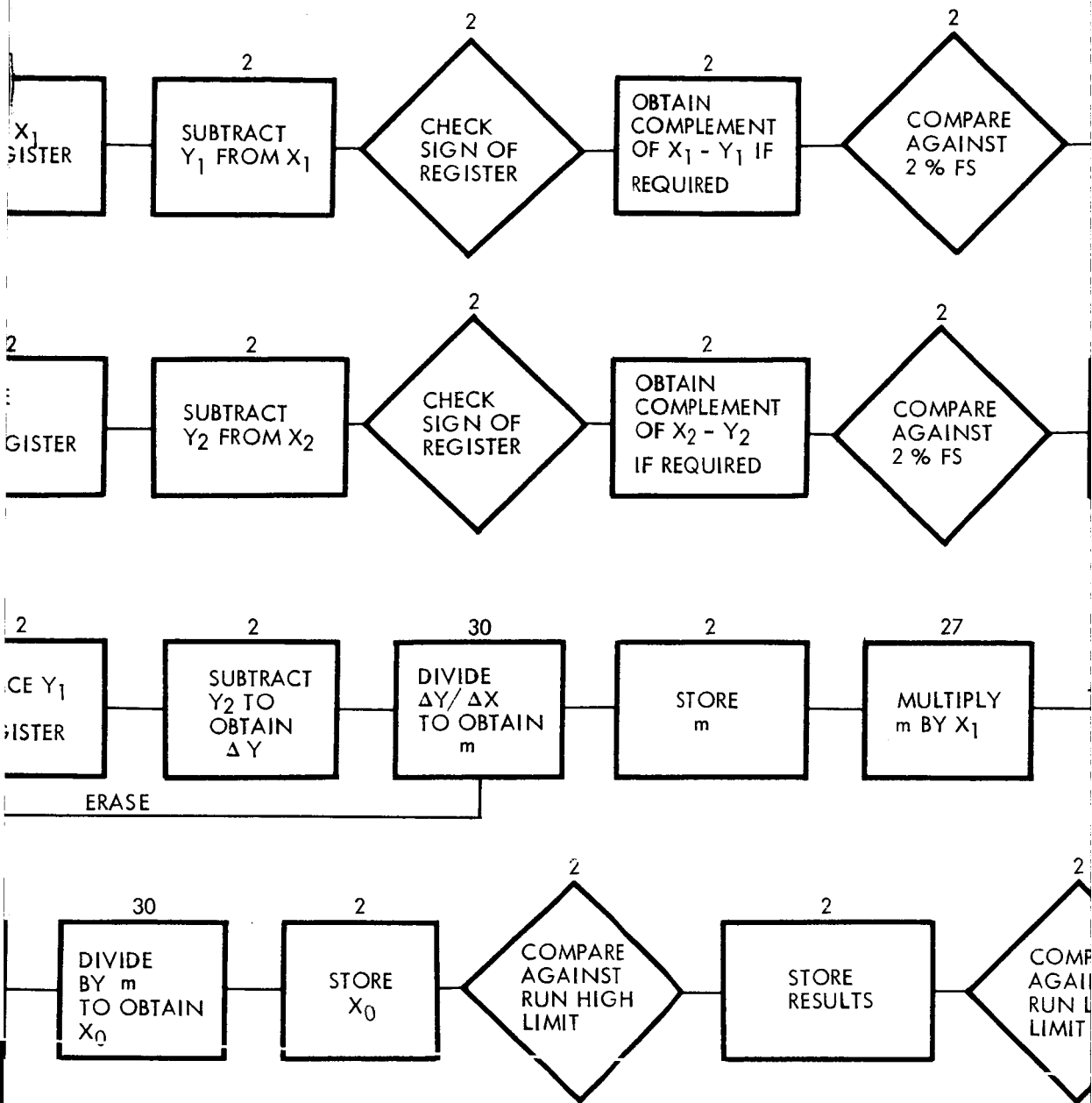
First, the checkpoint is programmed through RACS. The computer then acquires the high checkpoint measured value. The next computer step subtracts 24 bits (the DDAS offset) from the measured value. This measured checkpoint value (Y_1) next is stored in the computer's temporary memory. Following this, the high checkpoint predetermined value (X_1) is placed in the register where Y_1 is subtracted from it. The sign of the register is then checked; if the sign is negative, the complement of $X_1 - Y_1$ must be obtained. The absolute value of $X_1 - Y_1$ is compared against 2 percent full scale and the status is stored in the memory. The absolute value of $X_1 - Y_1$ then is compared against 10 percent full scale, with this status stored in memory. Any value within the 2 percent tolerance range is considered definitely Go; any value between 2 percent and 10 percent is considered marginal and must be evaluated by engineering. The total time for the computer to process a high checkpoint value is a minimum of



RCA 110A WORD TIME 28.85 MICRO ACCORDS.

NUM

20 ①



NUMBERS ABOVE BLOCKS DENOTE WORD (CYCLE) TIMES FOR THE RCA 110A COMPUTER

20 (2)

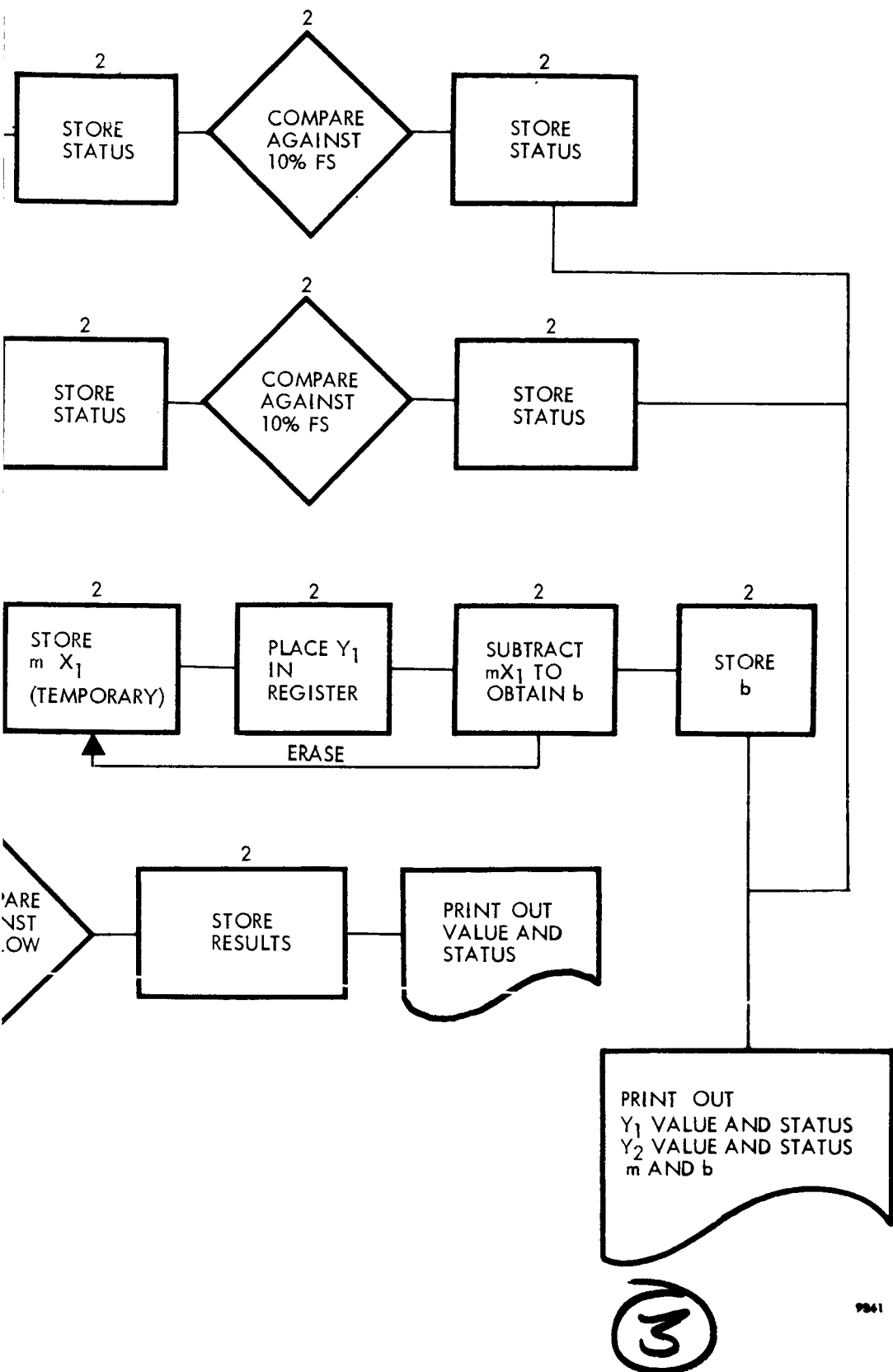


Figure 4. OPERATION TO PROCESS
ONE SIGNAL MEASUREMENT

34 word times or 980.9 microseconds. After completion of the high checkpoint evaluation, the low checkpoint measurement is processed through the computer. The procedure for processing the low checkpoint measurement is similar to that described for the high checkpoint measurement. Here again the minimum processing time would be 980.9 microseconds. Upon completion of both high and low checkpoints, the correction factors are computed. The predetermined high checkpoint value (X_1) is placed in the register where X_2 , the predetermined low checkpoint value, is subtracted from it. The resultant value, ΔX , is stored in temporary memory. The measured high value, Y_1 , is pulled from memory and placed in the register where Y_2 , the measured low value, is subtracted from it to obtain ΔY . The resultant value of ΔY is divided by ΔX to obtain the value m , the gain correction factor, which then is stored for later printout and application to "run" data. This value of m is then multiplied by X_1 , and the resulting value, mX , is stored. Y_1 is pulled from storage and entered into the register where mX is subtracted from it to obtain b , the offset correction. The value b is put into storage for later use. Minimum time to compute correction factors is 2111.45 microseconds. At this time Y_1 , Y_2 , m , b , and the two status values (± 2 percent, ± 10 percent) can be pulled from storage and printed out. After completing the correction factor computation, the computer next programs the "run" values through RACS. The measured sensor value is acquired and 24 bits (DDAS offset) is subtracted from it to obtain Y_0 . The offset correction factor, b , is pulled from storage and subtracted from Y_0 . This resultant value is then divided by the gain correction factor, m , to obtain X_0 , the corrected sensor signal. The corrected sensor signal is stored for later printout. The corrected sensor signal next is compared with both the run mode high limit with the results being stored, and the run mode low limit with the results being stored. The value and status of the sensor measurement can be printed out. Time to program the run value through the computer is 1384.8 microseconds. The minimum computer time required to process one channel through calibration and to obtain the corrected value less printout is 5458.05 microseconds. Additional time requirements to process signals is a distinct possibility. Figuring the base minimum of 5458.05 microseconds to process one corrected signal less printout, and the theoretical maximum number of signals to be processed as 1458, the total computer time involved would be 7.9578×10^6 microseconds, or roughly, 8 seconds. Other computer types with shorter cycle times can process these signals more rapidly.

The present method of computer checkout of the Saturn system requires 12 data memory locations per measurement channel. ACT requires an additional five data memory

locations per measurement channel or a total of 17 locations. The following table shows a comparison of the data memory locations for ACT and the current method, for one measurement channel.

COMPARISON OF DATA MEMORY REQUIREMENTS PER MEASUREMENT CHANNEL
ACT VERSUS PRESENT METHOD

ITEM NO.	NAME	SYMBOL	ACT	PRESENT METHOD
1	Measurement Channel Number	-	X	X
2	Predetermined High Checkpoint Value	X_1	X	X
3	Predetermined Low Checkpoint Value	X_2	X	X
4	Measured High Checkpoint Value	Y_1	X	X
5	Measured High Checkpoint $\pm 2\%$ Tolerance Status (Go Condition)	$Y_1 \pm 2\%$	X	X
6	Measured High Checkpoint $\pm 10\%$ Tolerance Status (Marginal Condition)	$Y_1 \pm 10\%$	X	
7	Measured Low Checkpoint Value	Y_2	X	X
8	Measured Low Checkpoint $\pm 2\%$ Tolerance Status	$Y_2 \pm 2\%$	X	
9	Measured Low Checkpoint $\pm 4\%$ Tolerance Status	$Y_2 \pm 4\%$		X
10	Measured Low Checkpoint $\pm 10\%$ Tolerance Status	$Y_2 \pm 10\%$	X	
11	Gain Correction Factor	m	X	
12	Offset Correction Factor	b	X	
13	Measured Sensor Value (Run Mode)	Y_0	X	X
14	Corrected Sensor Value	X_0	X	
15	Run High Tolerance Limit	-	X	X
16	Run Low Tolerance Limit	-	X	X
17	Run High Tolerance Comparison Result	-	X	X
18	Run Low Tolerance Comparison Result	-	<u>X</u>	<u>X</u>
Total Memory Slots			17	12

The current configuration of the Saturn program does not use the maximum capability of the DDAS.

On Saturn IB-1, the booster and IU have 700 measurement channels. Of these channels, 467 are compatible with ACT. The balance of 233 are not considered compatible because they lack provisions for programming the insertion of known input values.

For computer checkout and calibration unification without ACT, the booster and IU require 8400 computer data memory locations and approximately 2000 instruction memory locations.

For calibration and checkout with ACT, 7939 data memory locations are required for the compatible signals and 2796 locations are required for the noncompatible signals for a total of 10,735 data memory locations. In addition, approximately 2500 instructions are required for a total of 13,235 memory locations.

If 1000 data channels are used on a PCM system, 540 (27 racks of 20 channels each) can be compatible with ACT. This would require 17,100 data and instruction locations.

The magnetic tape data output from the computer is one of the time limiting factors. The RCA 110A has an output rate of 15,000 characters per second.

SECTION 6

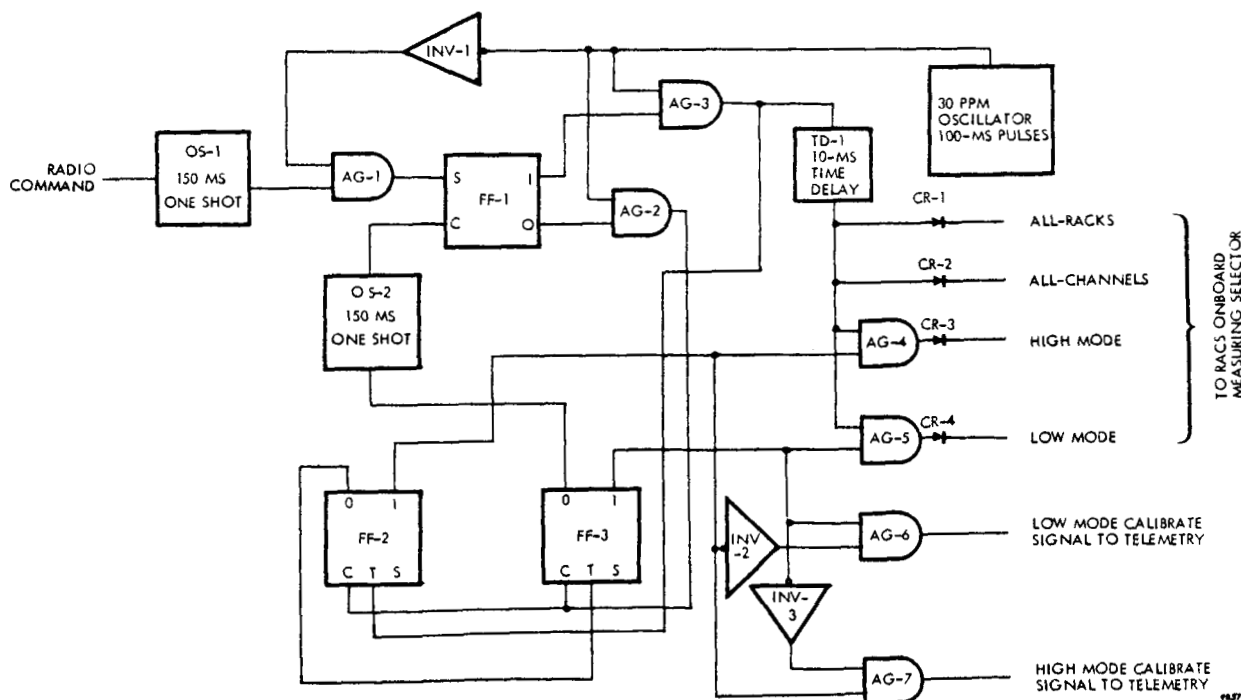
ONBOARD PROGRAMMER

The application of ACT, primarily, has dealt with ground-based vehicles. However, the technique is equally applicable to remote or orbiting vehicles, provided a means of initiation and identification of the calibration data is provided. The simplest means of implementation is to install an onboard programmer activated by the radio command link. This programmer must provide signals, through the data retrieval system, to advise ground-based computers of the calibration mode, as well as activate the calibration cycle.

A closed-loop type system - where the ground computer prepares itself to process calibration data, issues a calibration command, awaits data, and then processes the data - is not practical on remote space vehicles. For a vehicle on the surface of the moon, the time interval for the command signal to be transmitted and the data received, disregarding any onboard programming sequences, would be 2.65 seconds.

To minimize the complexity of the onboard programmer, all measurement channels are programmed simultaneously through the high-calibrate, low-calibrate, and the run mode when airborne. This calibration cycle can be achieved in a maximum of 4.1 seconds after receipt of the calibration command from the command receiver. An additional 2 seconds is required to permit the programmer to reset for another calibration command. Switching from one mode to the next is accomplished at 2-second intervals. As no synchronization with the PCM wave train is used, four of the eight DDAS wave trains that occur during a 2-second-time-period mode are required for switching, two for the onboard program, and two for the computer identification of mode. The computer delays the acquisition of data for one complete wave train, storing the information from the sixth and seventh wave trains of a calibration mode period. The eighth wave train is not used. The delay in the computer compensates for the operation time of the RACS control and relays within the signal conditioners.

Figure 5 depicts the logic diagram for the onboard programmer. A single pulse input to the onboard programmer is required from the radio command receiver. Six outputs from the programmer exist. Four of these outputs are connected, through isolation diodes, to the RACS onboard measuring rack selector inputs. The other two outputs are connected to PCM/DDAS discrete word segments. The four signal lines connecting to the RACS Measuring Rack Selector are:



Assuming the programmer to be in the noncalibrate mode, the following quiescent conditions exist. FF-1, FF-2, and FF-3 are in the clear condition (output on 0). AND gates AG-1, AG-3, AG-4, AG-5, AG-6, and AG-7 are closed. AG-2 is open, allowing the 30-pulse-per-minute, 100-millisecond-duration pulses from the oscillator to keep FF-2 and FF-3 in the reset condition.

When a radio command calibrate signal is received, the 150-millisecond one-shot OS-1 pulses. If this pulse occurs simultaneously with or during the time of the 30-ppm pulse from the oscillator, AG-1 remains closed due to the action of the inverter INV-1. Should there not be an output from the oscillator, FF-1 will be turned on only during the 1900-millisecond period that the oscillator pulse is off. This is to ensure that full length pulses from the oscillator are available for operating the control lines to the RACS equipment. RACS commands must have a minimum duration of 50 milliseconds.

When FF-1 sets, AG-2 closes and AG-3 will open whenever a pulse from the oscillator occurs. The first oscillator pulse is then fed to the trigger of FF-2 and the all-racks output, the all-channels output, AG-4, and AG-5 through the 10-millisecond time delay TD-1. FF-2 flips to set, enabling AG-4, the high mode RACS command, during the duration of the oscillator pulse. AND gate, AG-7, will open as FF-2 is in the set condition, and FF-3 is clear which applies signals to both inputs of AG-7. AG-7 will remain open as long as FF-2 is set, and FF-3 is clear. The second pulse from the oscillator through AG-3 causes FF-2 to clear which in turn triggers FF-3, causing it to set.

When FF-2 clears, AG-4 and AG-7 are inhibited, and AG-6 has a signal applied through INV 6-2. FF-3, when in the set condition, applies signals to AG-5 and AG-6, and an inhibit to AG-7 through INV-3. AG-6 now opens, applying a signal to the low-mode calibrate signal to telemetry. The second pulse from the output of AG-3 also applies 100-millisecond pulse through TD-1 to all-racks, all-channels, and through AG-5 to the low-mode output.

The third pulse from AG-3 causes FF-2 to flip to the set condition, thus applying 100-millisecond pulses to AG-4 and AG-5, high-mode and low-mode outputs respectively, as well as to the all-racks and all-channels outputs. Because FF-2 and FF-3 are both set, AG-6 and AG-7 are both inhibited through INV-2 and INV-3 respectively.

The fourth pulse through AG-3 triggers FF-2 to clear, which in turn triggers FF-3 to clear. When FF-3 clears, a pulse through one-shot OS-2 clears FF-1 causing AG-3 to inhibit further oscillator pulses from triggering FF-2. AG-2 will now conduct on all oscillator pulses, keeping FF-2 and FF-3 continuously clear. The function of TD-1 is to delay the initiation of pulses to the RACS until FF-2 and FF-3 have had an opportunity to flip to the desired state.

Figure 6 depicts the timing chart for the onboard programmer. The calibration mode initiates during the off time of the programmer oscillator (30 ppm of 100-millisecond duration pulse). Coincident with the first oscillator pulse, the high-mode telemetry discrete signal is generated. Following a 10-millisecond delay, the all-racks, all-channels, and high-calibrate mode signals, of 100 milliseconds duration, are supplied to the RACS inputs. Coincident with the second oscillator pulse, the high-mode telemetry discrete switches off and the low-mode telemetry discrete switches on. Following a 10-millisecond delay, the all-racks, all-channels, and low-calibrate mode commands are supplied to RACS. Coincident with the third oscillator pulse, the low-mode telemetry discrete signal turns off. Following another 10-millisecond delay, the all-racks, all-channels, high-calibrate mode and low-calibrate mode commands are issued to RACS to return the system to the run mode. A fourth oscillator pulse is required to complete the reset cycle of the programmer.

The one disadvantage to programming all-racks and all-channels through the calibration mode simultaneously is the amount of power required to operate all the signal conditioner relays in the calibration modes. The RACS has the capability of controlling 27 measuring racks of 20 channels each for a total of 540 channels. Using a figure of 40-ma current drain per relay, the instantaneous current required to operate a maximum of 540 relays from a 28-volt source is 21.60 amperes. This power would be required for 2 seconds for each mode, or a total of 4 seconds, assuming that each signal conditioner had two modes. The total power required in ampere-hours, assuming a calibration cycle occurs once each hour, is

$$\frac{21.60 \text{ amperes} \times 4 \text{ seconds}}{3600 \text{ second/hour}} = 0.024 \text{ ampere/hour}$$

The ampere-hour requirement for calibration is relatively low. Should the electrical system be capable of withstanding the 4-second peak load of 21.60 amperes, no real problem exists.

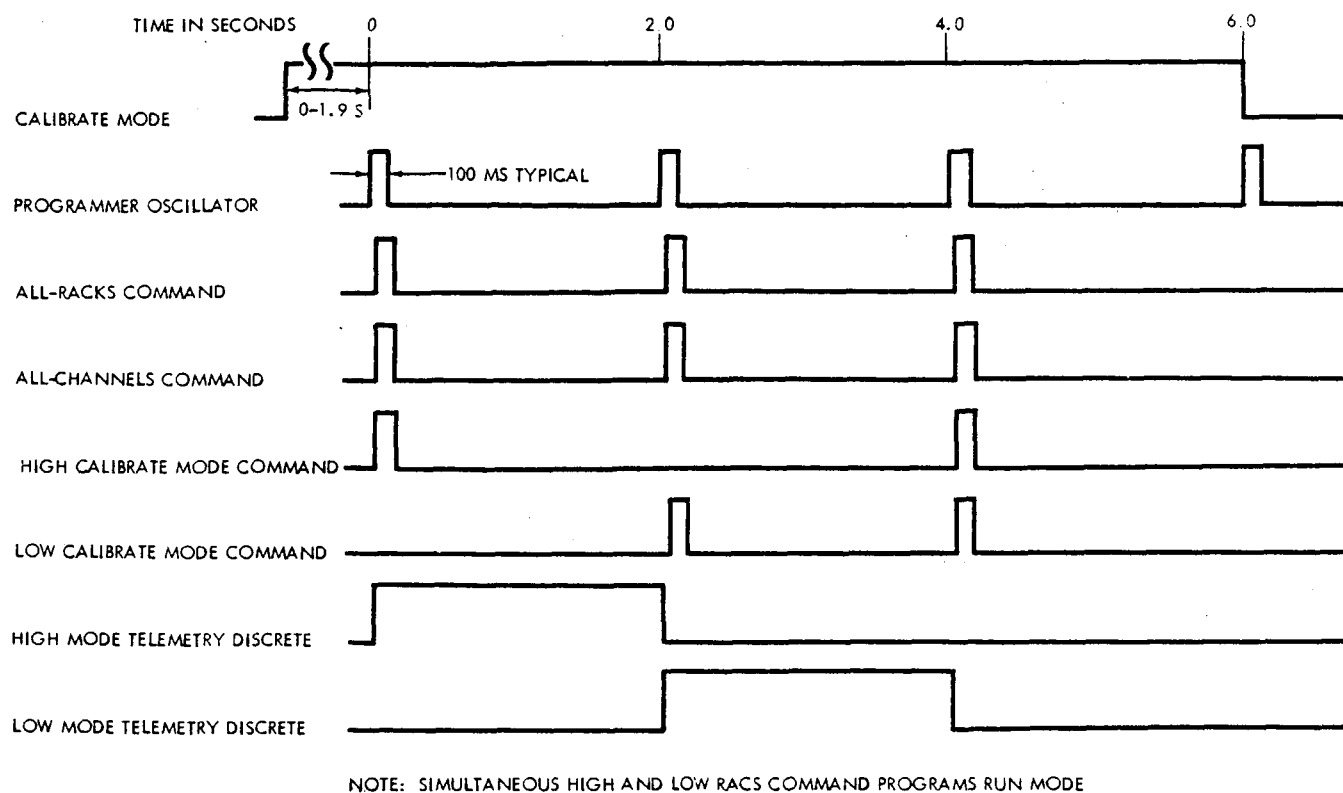


Figure 6. TIMING CHART-PROPOSED ONBOARD CALIBRATION PROGRAMMER

To decrease the instantaneous power load, keeping the same quantity of signal conditioners, a more complicated programmer could be developed that would sequence the racks or groups of racks. This has the added disadvantage that more telemetry discrete channels would be required to denote which channels are being calibrated. Also, the computer routines would become more complicated to identify and process the correct channels undergoing calibration.

SECTION 7

GROUND VERSUS ONBOARD CHECKOUT

The MSFC's Automation Plan, revised 1 June 1964, under Future Trends, indicates the ultimate solution to the checkout problem may be the utilization of an onboard computer. Stated therein is the following: "This computer would have a stored program which describes the flight-path to satisfactory mission completion. This computer would receive inputs from guidance sensors which would be utilized with vehicle condition sensors and compared with performance requirements to provide an assessment of mission accomplishments."

"Checkout for this vehicle would require a ground computer to interrogate the onboard computer as to vehicle readiness. The only signal necessary in reply would be 'Vehicle is ready and capable of mission accomplishment' or 'Vehicle is not ready'."

The onboard computer has many advantages over the ground-based computer, but it also has many disadvantages.

Advantages to an onboard checkout computer system are:

- (1) Decrease in ground checkout equipment
- (2) All sequences in checkout utilize the same equipment. Checkout after manufacture, post-static, and prelaunch is identical.
- (3) Standardization of procedures and methods with a resultant increase in the correlation of results

- (4) Decrease in documentation - The design group responsible for the vehicle is now responsible for computer programming. The change release for the vehicle includes programming changes.
- (5) Decrease in computer software - Software for only one computer is required.
- (6) Decrease in umbilical connections
- (7) Provides onboard checkout for manned vehicle without addition of equipment.

The disadvantages of an onboard computer are:

- (1) Added vehicle weight
- (2) Added vehicle power consumption
- (3) Decrease in vehicle reliability
- (4) Costs for development and flight qualification of a new computer
- (5) Increased vehicle costs
- (6) The probability that each stage would require a different computer configuration is a distinct possibility.

The present vehicles interface with the ESE through RACS and DDAS for primary system calibration and verification. These two subsystems are the only subsystems that are common to all stages at all facilities within the Saturn program. A more logical approach to vehicle checkout would be to combine the advantages of ground-based checkout with the advantages of onboard checkout in a common type ground-based computer. This new computer would make a third subsystem common to all stages and all locations. The computer could be associated with a particular stage, traveling between facilities as part of the vehicle software package, or it could remain at a given location and programming tapes could travel with the vehicle package. Used in this manner, the computer would not add weight to the vehicle, decrease the vehicle reliability, consume vehicle power, or increase the vehicle cost.

Design responsibility for the computer programming should be assigned to the design group of the onboard hardware, just like it would be assigned for an onboard computer. Thus, when a change is made to the onboard system, the design release package would contain the information for the computer programming change. The computer is also reusable, which is not the case for an airborne computer. Increased flexibility in checkout is also obtained. By substitution of a programming tape, the computer can be used to monitor the performance of another stage. This common type computer is a digital processing device; therefore, identical results with two like computers would be obtained if the same inputs were supplied. In event of a time consuming malfunction at the launch site, the system tested by the malfunctioning unit could be tested by tape substitution. There are several off-the-shelf small general purpose computers, which sell for under \$150,000, that can perform the evaluation of vehicle performance. These computers have the capability of adequate storage for ACT and the ability to perform the necessary calculations. These same computers, while not having the capability of the RCA 110A for multipurpose control, can perform the arithmetic computations much more rapidly; cycle time of 1.75 microseconds are common. Multiplication and division execution times are 8.75 and 22.75 microseconds respectively, thus permitting real-time corrections and limiting evaluation of sensor data. At the launch facility, the new computer would perform under control of the RCA 110A computer complex. This would also relieve much of the expected overload on the RCA 110A. Since data can be routed to the computer over r-f links as well as hardwire, all signals can be real-time monitored in flight for true system performance evaluation. Corrective action as required then can be taken.

The use of an external computer requires a minimum of three wires, plus a ground return, through the umbilical. These wires are high-calibrate mode, low-calibrate mode, and the coax cable containing the 600-kc information from the vehicle to the ground DDAS. Since calibration of the onboard system can be accomplished in a relatively short time, all channels can be switched through the various calibration modes simultaneously. There is now no requirement for RACS as presently known on board the vehicle. To properly adjust the block house real-time display meters and chart recorders, however, the calibration mode should be applied for sufficient duration to permit the adjustment of the meters and chart recorders.

With an onboard computer the same requirements for adjustment of the block house real-time display meters and recorders exist. Both high and low modes must be programmed for display calibration.

In addition, with an onboard computer, umbilical wiring will be required to provide print-out of the measured values from the computer.

While these computers will evaluate all instrumentation functions relative to manned spacecraft capsules, a separate onboard computer is recommended to evaluate only those measurements pertaining to safety and control functions and present the results to the astronauts. This onboard computer is discussed further in Section 9, Manned Vehicle Checkout.

SECTION 8

UNMANNED VEHICLE CHECKOUT

Figure 7 shows a block diagram for an unmanned spacecraft containing the capability of remote calibration of the vehicle instrumentation. Prior to vehicle launch, calibration of the system is performed through RACS in the conventional manner. Once the spacecraft is airborne, subsequent calibrations are performed via radio command. To provide this capability, all that is required is the addition of a simple programmer between the command receiver and the onboard RACS system.

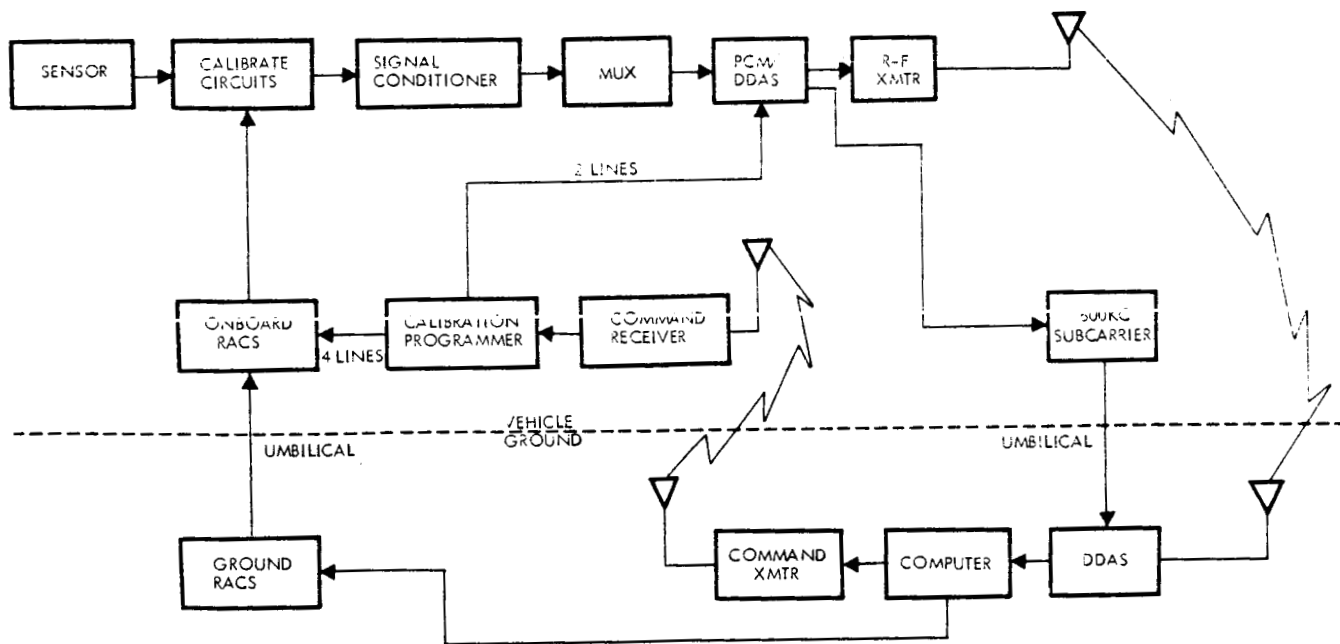


Figure 7. CALIBRATION CONTROL FOR UNMANNED ORBITING VEHICLES

The computer issues a command to the vehicle through the radio command link. The calibration programmer switches the high and low checkpoints in sequence through the onboard RACS units. Simultaneously with the switching, the appropriate mode discrete signal is supplied to the PCM/DDAS assembly for insertion into the DDAS wave train. The DDAS wave train is received by the ground DDAS system and fed to the computer in the proper sequence. The computer recognizes the calibration mode discrete and initiates a priority interrupt routine to store new measured values for the checkpoints. Following the accumulation of both checkpoints, new corrections are generated. Following the completion of the generation of one new correction factor, the computer applies the new factors to all subsequent sensor data. Because of the use of a fast computer, the correction factors can be generated essentially in real time, thus not costing a loss in data.

SECTION 9

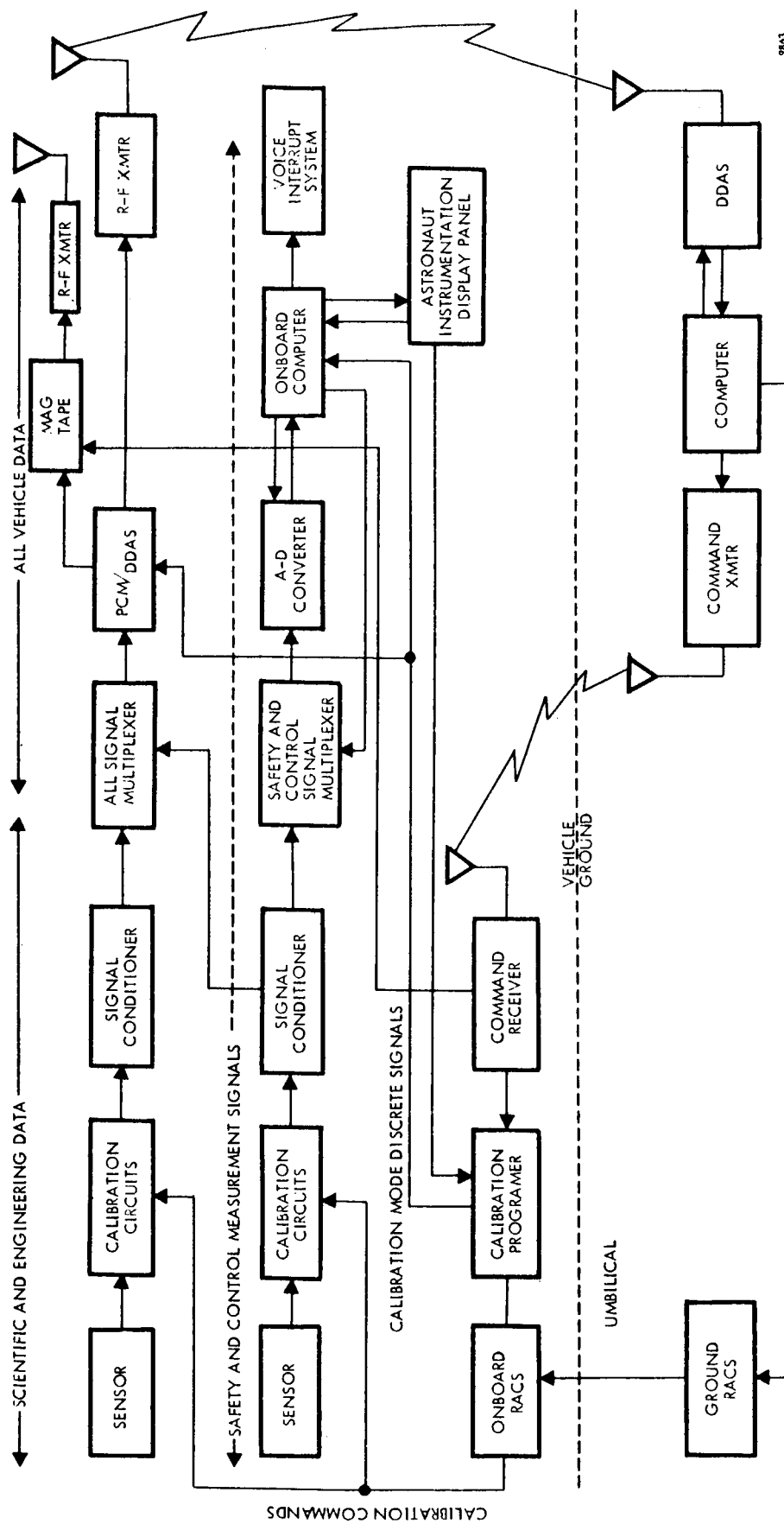
MANNED VEHICLE CHECKOUT

Manned spacecraft capsules have a large magnitude of data to be derived. This data can be grouped into two general classifications; those measurements that affect safety and control of the capsule, and those measurements containing data of an engineering or experimental nature. Because safety and control is of primary interest to the astronauts, it is recommended that they concern themselves only with these measurements. Their task is burdensome enough without having to worry about the latter group of measurements. If this philosophy is imposed, it is believed a relatively small (99 channels) onboard computer can be provided for these functions. Figure 8 shows a block diagram that expands on this concept.

Safety and control measurements are multiplexed into an A-D converter to an onboard computer. In addition, these same measurements are multiplexed into the PCM/DDAS channel, that contains all of the vehicle instrumentation measurements, for transmission to ground-based telemetry stations.

The PCM/DDAS signals from the manned spacecraft are treated in much the same manner as those for an unmanned vehicle. Each stage has associated with it a ground-based computer that is treated as part of the vehicle software.

For vehicles that are expected to be out of telemetry range of ground stations, such as on the far side of the moon, an onboard recorder activated by loss of carrier by the command receiver records the telemetry PCM/DDAS data. Upon return of vehicle reception of command link, the onboard tape recorder plays back, to the ground station, the recorded information on a separate r-f link. The separate r-f link permits simultaneous recording of real-time telemetry plus the delayed tape playback.



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Figure 8. INSTRUMENTATION CHECKOUT SYSTEM FOR MANNED SPACECRAFT

The multiplexer, A-D converter, and computer associated with the safety and control measurements are synchronized. The 99 channels are scanned once a second with the output of the computer presented on the Astronauts Instrumentation Display Panel. An audible voice interrupt priority system alerts the astronauts to any signal that exceeds its limits.

The computer directs the multiplexer scan and causes the A-D converter to digitize the telemetry voltage. Since the multiplexer, A-D converter, and computer operate in synchronization, no offset similar to that used in the PCM/DDAS is required. The A-D converter converts the 0- to 5-volt telemetry to 0 to 999 binary values, consisting of 10 bits in parallel. Once digitized, the binary values are equivalent to percent full scale.

The computer has the ACT capability and therefore applies correction factors to the measured values to present true sensor values in terms of percent full scale at the Astronauts Instrumentation Display Panel. To the engineer intimately familiar with the 0- to 5-volt terminology associated with telemetry this might at first be confusing, but to a pilot, a percentage full scale would be more meaningful than the telemetry value.

Primary prelaunch checkout of the signal conditioner associated with the safety and control signals is performed via the PCM/DDAS link. For this reason, the onboard computer need not compare and store the measured value of the two checkpoints against a 10 percent limit. This, therefore, decreases the number of memory locations per measurement channel required within the computer from 17 to 15. For 100 channels, the onboard computer will require 1500 data locations. If 12 bit words are used, the memory would require 4096 locations to provide adequate instructions.

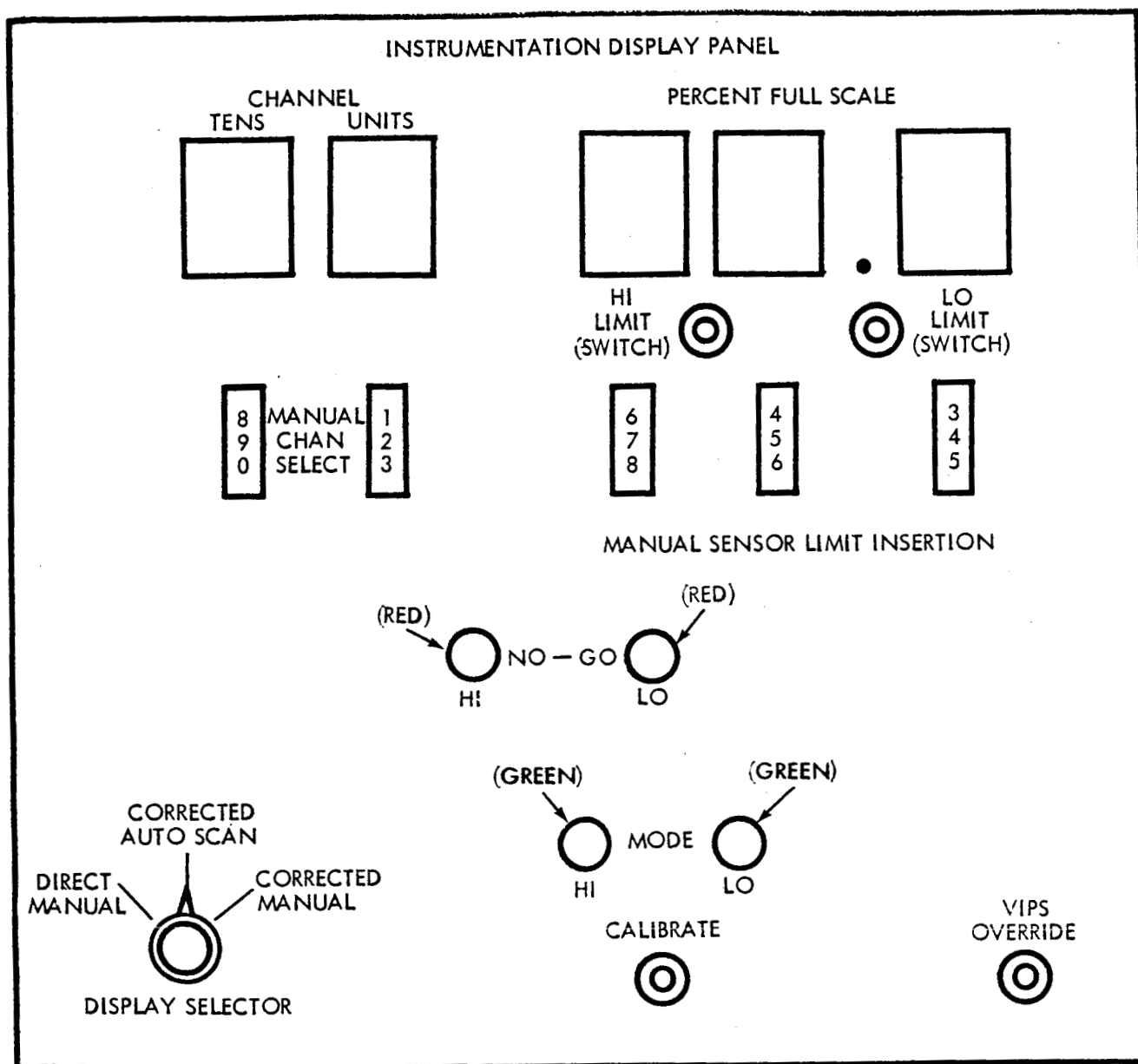
The calibrate mode can be initiated by either radio command or by the astronauts from their Instrumentation Display Panel. Both the safety and control system and the conventional PCM/DDAS enter the calibrate mode simultaneously. Upon acquisition of both the high and low checkpoint measured values, the onboard computer compares the measured values in real time and stores the results of the comparison. Following the comparison of all the low checkpoint values, the computer scans the high-mode and low-mode comparison results in sequence. If an out-of-tolerance (greater than ± 2 percent) condition exists, the computer displays the measured

value, channel number, and high or low No-Go on the display panel for a minimum of 3 seconds. Each No-Go is displayed in sequence. In the absence of No-Go's, or during the presentation of the first No-Go, the computer generates and stores new correction factors for all channels. Upon completion of the correction factor generation, and return of all signal conditioners to the run mode, the computer corrects all run values in real time and compares them against the prestored tolerance limits for the sensor values.

If out-of-tolerance sensor measurements are encountered, the computer provides a display of the channel number, corrected measurement value, and No-Go high or low on the Instrumentation Display Panel.

The voice interrupt priority system provides an audible indication to the astronauts in the event of the detection of an out-of-tolerance sensor measurement. Should the astronauts be concentrating on some operation and fail to see a No-Go warning light, the voice interrupt priority system initiates a prerecorded message that advises them of the out-of-tolerance condition and what corrective action should be taken. If two or more out-of-tolerance conditions occur simultaneously, the most critical condition assumes priority and its message of corrective action takes precedence. As corrective action or astronaut override occurs, the next most serious message action is presented. Upon successive corrective action or override, the next least serious condition is reported until all problems have been cleared or overridden. The voice interrupt priority system operates independent of the Astronauts Instrumentation Display Panel selector switch. Should the astronauts be monitoring a particular channel and another channel exceeds its tolerance limits, the astronauts receive an audible indication that the other channel has an out-of-tolerance condition.

The Astronauts Instrumentation Display Panel (figure 9) is composed of a two-digit channel indicator (99-total-channel capacity) with two manual thumbwheel-type selectors (one for tens, the other for units); a three-digit percent of full scale readout indicator (00.0 to 99.9); three manual thumbwheel-type selectors for manual sensor limit insertion; high limit and low limit insertion switches; a three-position display selector switch; an on-off calibrate pushbutton; two NO-GO indicators, one for high and one for low; two calibrate mode indicators, one for high and one for low; and voice interrupt priority system override. The absence of either calibrate mode indication means the system is in run mode. In the run mode, the DISPLAY SELECTOR



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Figure 9. ASTRONAUT INSTRUMENTATION DISPLAY PANEL

switch may be set in any of its three positions. If it is set at CORRECTED AUTO SCAN, and all measurements are within tolerance, the digital indicators will all display zeros. But if a measurement is detected as being out of tolerance, the CHANNEL indicator will display the malfunctioning channel number, the PERCENT FULL SCALE indicator will show the corrected measurement value, and the applicable NO-GO indicator will light, depending upon the high or low tolerance variance. These indicators will display for at least 3 seconds, giving the astronaut time to note the indicated channel corrected measurement, and the applicable NO-GO indication. He then can turn the DISPLAY SELECTOR switch to DIRECT MANUAL, and MANUAL CHAN

SELECT thumbwheel selector to the applicable channel for a continuous actual measurement reading on the PERCENT FULL SCALE indicator. The applicable NO-GO indicator will remain lighted. The astronaut may use this information to compare with a redundant instrument elsewhere in the spacecraft and/or with the corrected measurement reading. He then can turn the DISPLAY SELECTOR switch to CORRECTED MANUAL, and the MANUAL CHAN SELECT thumbwheel selector to the applicable channel. This will give a continuous readout of the PERCENT FULL SCALE indicator of the corrected measurement. The applicable NO-GO indicator also will remain lighted. He then can compare the actual measurement readout with the corrected measurement readout.

All digital readouts are displayed for 3 seconds to permit the astronauts time to acquire and comprehend the value. Continuous monitoring of one channel is updated once every 3 seconds.

New sensor limits can be manually inserted into the computer by setting the five thumbwheel switches to the desired channel number and percent full scale value and depressing the appropriate high or low limit switch.

SECTION 10

RECOMMENDATIONS

The recommendations contained in this report include the recommendations contained in both the Phase B and Phase C-1 reports submitted previously to NASA. These recommendations are as follows:

- (1) Demonstration of ACT - During the course of investigation numerous contacts were made with the stage contractors of the Saturn Program. All expressed a desire to witness a demonstration of the ACT under operational conditions. Such a demonstration should be given. Manufacturing and engineering representatives of the Saturn stage contractors and key personnel from the various NASA divisions should be invited to witness the demonstrations so a high level of confidence in the ACT concept can be established.
- (2) Data Evaluation - A program for the evaluation of data acquired during the sequences of checkout should be established. Because signal conditioners are not adjusted after installation, ACT permits the accumulation of meaningful data that will establish a level of confidence for the attainment of a vehicle mission. This program should investigate the various contractors' data accumulation facilities, establish a compatible format for data recording and analysis, and ensure that the timely dissemination of results to launch facility and the responsible design groups is accomplished.
- (3) 115-Volt Reference - Reference voltage for the a-c signal conditioners is derived from the 115-volt a-c bus. The bus voltage is supplied either from the inverter in the IU or from a ground power source. It is recommended that the bus be monitored in order that a correction factor can be determined during the calibration run. As an alternate to monitoring the bus,

the worst case conditions can be established experimentally, and the tolerances relaxed accordingly.

- (4) Thermocouple Signal Conditioner Calibration - NASA engineers have reported that an error can be introduced into thermocouple signal conditioners when the thermocouple and the reference junction are at relatively high differential temperatures. This is due to the fact that the relay shorting contacts do not provide an absolute short across the thermocouple. It is recommended that a small resistor, 1 to 10 ohms, be added in the return leg of the thermocouple. This would provide a load for the thermocouple during calibration, thus minimizing the effect of not having an absolute short. Compensation for the slight effect of the added resistor can be accomplished by selection of the calibration bridge values.
- (5) Real-Time Meter Displays - The real-time meter displays to be used in the Saturn IB program at Kennedy Space Center and IBM do not provide adequate adjustment compatible with ACT. It is recommended that the circuitry provided in the Interim Report - Investigation of Real-Time Displays, Northrop Nortronics letter Y4411-5-143 ATEU/IAS:mr, dated 15 June 1965, for real-time meters be incorporated.
- (6) Onboard Calibration Programmer - It is recommended that an onboard calibration programmer be developed that is activated by radio command along the lines discussed in this report. This prototype programmer should be installed on a Saturn IB, and after vehicle separation, activated to obtain calibration data. This will prove the feasibility of the onboard programmer and also permit a better performance evaluation of the booster instrumentation.
- (7) Considerations of Onboard Versus Ground Computers - This report has shown that a ground-based computer is more efficient than an onboard computer for vehicle checkout. It is strongly recommended that the findings of this report receive thorough evaluation.
- (8) Onboard Computer - For manned spacecraft, NASA should consider incorporation of a small onboard computer test system for safety and control measurements. This computer test system should be limited to 99 channels.

- (9) Voice Interrupt Priority System - This voice warning system should be added to the manned spacecraft to aid the astronauts in determining malfunctions and advising them as to what corrective action must be undertaken to alleviate the problem.